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CRUSTAL STRUCTURE IN WAKAYAMA DISTRICT AS DEDUCED FROM LOCAL AND NEAR EARTHQUAKE OBSERVATIONS

BY

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Abstract

The crustal structure in Wakayama District was derived from close observations of local and near earthquakes at network stations spread over the area. Laboratory experiment on bed rocks was also made to get reference data on seismic velocities.

The propagation velocities of the *P*- and *S*-waves and the layer thickness obtained, are : $V_p=4.3$ km/sec, $V_s=2.4$ km/sec, $h_1=4$ km for the sedimentary layer, $V_p=5.5$ km/sec, $V_s=3.2$ km/sec, $h_2=7$ km for the granitic layer, $V_p=6.1$ km/sec, $V_s=3.5$ km/sec, $h_3=15$ km for the basaltic layer, and $V_p=8.0$ km/sec, $V_s=4.5$ km/sec for the mantle surface, respectively. The crustal depth to the Mohorovičić discontinuity in this region is estimated to be about 26 km.

The spatial distribution of foci of micro-earthquakes in the northern part of the district, is confined above the granitic layer.

1. Introduction

Seismometric studies on the structure of the earth's crust have successfully been made by many seismologists from various standpoints since the earlier days of the present century. As a result of these excellent investigations, considerable part of the secrets about the physical properties of the crust has certainly been brought to light, although some problems remain unsolved.

With the recent advance of the observation technique and accuracy, the detailed regional character of the crust and its relation with the conditions of earthquake occurrence, came to be an attractive subject of research, not only in the studies of natural earthquakes but in explosion seismology. As one of the ways to pursue solution of the problems, close and intensive observations of local and near earthquakes are required.

As is well known, in Wakayama District, Japan, micro-earthquakes have frequently occurred with diversity in location and variation in frequency of their generation. The vicissitudes of these local shocks may probably be related with the crustal deformation in the Kii Peninsula. Hence, the crustal structure in the region must be investigated in connection with the crustal deformation by effectual methods.

A. Imamura and others made the first systematic observation of "miniature earthquakes" in this region in 1929[1]. Since 1952, the Geophysical Institute of Kyoto University, in co-operation with the Earthquake Research Institute of Tokyo University, has effectively observed local earthquake swarms at many network stations spread over the same area with highly sensitive seismometers of electromagnetic type[2]. The results obtained in the observations in 1954 and 1956[3] gave a clue to elucidation of the generation mechanism of the micro-earthquakes and the crustal structure in the said district.

For the purpose of clarifying and discussing in more detail unsolved questions, especially on the structure, seismometric observation on a large scale was executed in 1959. Special attention was paid in this case to observe near earthquakes as well as local shocks with high accuracy of time at dense net of stations, in order to get some definite informations on deep interior of the crust.

In the present paper, the results of three observations and laboratory experiments on rock samples collected in the region will be reported and discussed. The crustal structure will be revealed to some detailed extent by synthetic analysis of the results.

2. Further Observation in 1959

(1) *Seismometric observation*

With a view to ascertain the previous findings, which were obtained in the past two experiments, and to get more available data, a third time observation of local shocks and near quakes was carried out at four stations established temporarily in Wakayama region from August 10th to 31st in

1959. Emphasis was laid, in the present case, on studying the fine crustal structure. Positions of the observation stations are shown in Table 1 and Fig. 1. These stations, except one at Shimotsu, were set up at the same

Table 1. Observation Stations established in 1959.

Station	Location		Elevat.	Coordinates	
	λ	φ	h	X	Y
Wakanoura (W)	135°10′04″E	34°11′23″N	35 m	0 km	0 km
Idakiso (I)	15 14	11 53	35	−0.91	7.90
Nokami (N)	17 50	09 47	80	2.99	11.76
Shimotsu (S)	10 06	06 19	40	9.26	−0.12

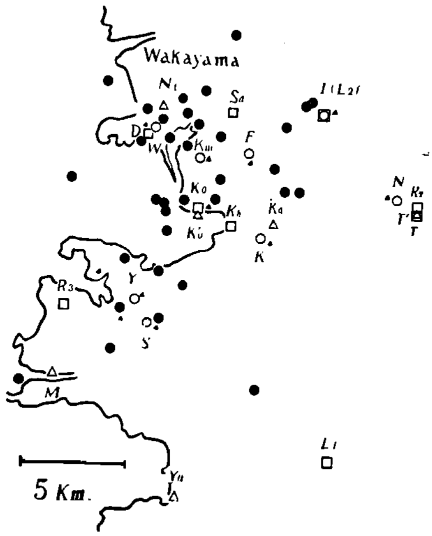


Fig. 1. Location of observation stations and epicentres of local shocks in 1954, 1956 and 1959 observations.
○ ; observation stations of the Kyoto University.
□, △ ; observation stations of the Earthquake Research Institute.
● ; epicentres.
▲ ; spots where rock samples were collected.

points as in the last observation. The coordinates were determined as follows, taking Wakanoura as the origin, southwards as the X-axis and eastwards as the Y-axis.

Observation techniques were, for the greater part, the same as stated in the previous paper[3], but in this case two electromagnetic seismometers of horizontal component were installed at all stations, while a vertical seismometer was used at most of observatories last time. The JJY standard time signals were marked every second on oscillogram rotating nearly 5 mm in a second.

During the observational period, 32 local shocks with $P\sim S$ duration times of less than 5 sec, and 6 near earthquakes with those of longer than 6 sec, were well recorded concurrently at more than two of the four stations. The frequency spectrum of the $P \sim S$ intervals recorded at each station, shows that the highest frequency lies in the period of 0.5~1.5 sec at Wakanoura, 1.5~2.0 sec at Idakiso, 1.5~2.5 sec at Nokami and 1.0~1.5 sec at Shimotsu respectively.

(2) *Determination of local earthquake foci and the time-distance graphs*

Selecting 9 clearly recorded shocks out of the above, their foci were determined by use of the $P \sim S$ duration times at four stations, under an assumption of homogeneous medium. The locations are shown in Fig. 1 and Table 2. In addition, the observed data at the respective stations in the above 9 shocks recorded in the present experiment and 27 earthquakes in the last observations, are together tabulated in the annexed table.

Table 2. Position of foci and propagation velocities.

Shock No.	X (km)	Y (km)	Z (km)	k (km/sec)	V_p (km/sec)	V_s (km/sec)	V_p/V_s
314	0.35	−0.85	6.25	6.86	4.56	2.73	1.67
315	−1.40	1.25	7.50	6.38	4.64	2.68	1.73
320	−0.23	0.25	5.73	5.95	4.62	2.58	1.78
326	0.80	1.60	5.40	6.03	4.82	2.68	1.80
333	6.85	0.30	5.50	5.22	4.45	2.41	1.85
335	3.90	0.65	3.75	5.44	4.28	2.38	1.79
353	3.55	0.20	4.40	5.40	4.82	2.54	1.89
359	4.80	0.75	1.60	5.59	4.42	2.46	1.79
360	6.25	−0.95	5.60	6.32	4.50	2.54	1.71

For convenience' sake, the arrival times of the P- and S-waves were plotted against the hypocentral distance, instead of the epicentral, on a time-distance graph. In the present observation also, the travel time deviation[3] related with the push-pull distribution in seismic initial motions, was clearly observed, in spite of slightly lower time accuracy due to smaller number of stations than those in the previous experiments. In other words, the time-distance relation was represented as a straight line in 3 shocks in which the initial directions were the same sense at all stations. On the contrary, it could plausibly be divided into two groups differentiated by push and pull in the initial motions in 6 quakes. Fig. 2 illustrates

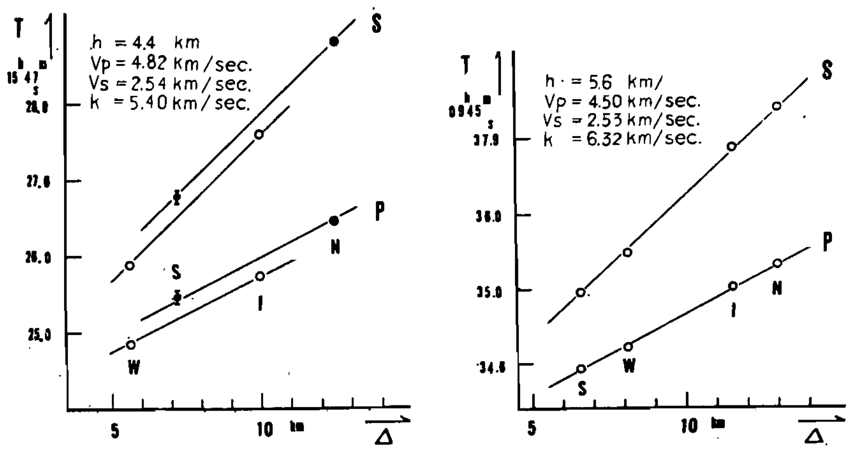


Fig. 2. Time-distance curves in two local shocks.

the travel-time curves of the two examples. The distance coefficient k, the propagation velocities V_p and V_s of the P- and S-waves, were estimated from the travel-time analysis.

When the $P \sim S$ times are taken as abscissa, instead of the hypocentral distance, the gradient of the straight line is expressed by $dT_p/dT_{s-p} = 1/(V_p/V_s - 1)$. That is, the velocity ratio of the P- and S-waves, or Poisson's ratio, can be estimated from the arrival times of both waves observed at two stations. As this method needs no assumption on a seismic focus and crustal structure, the errors attending determination of hypocentre will be excluded. This is, then, effectively used in research of the local character of the earth's crust from simple estimation of the said ratio[4,5,6].

Applying the above technique to our data in 32 shocks, the values of V_p/V_s are estimated to be from 1.6 to 1.9 in combination of two stations with the same sense in initial motions, while they show abnormal values for greater part of combination of any two stations with the opposite initial sense. This fact may support the afore-mentioned time anomalies.

(3) *Horizontal direction of initial motion*

The direction of approach of initial wave at each station can be derived from vectorial resultant of the initial amplitudes in two horizontal components. In the present case, the recorded amplitudes were corrected by the following experiment. In the respective systems, composed of a seismometer, galvanometer and shunt circuit, a constant infinitesimal displacement was given suddenly to the seismometer's pendulum by a certain small mass, and the amplitudes recorded on oscillogram were measured.

The direction thus estimated is not always in accord with the orientation connecting each station with an epicentre located by travel times of seismic waves. The epicentral orientation Φ_t measured counter-clockwise from eastward at each station and the deviation $\Delta\Phi_t$ are shown in Table 3.

Table 3. Deviation of horizontal direction of initial motion in local shocks.

Shock No.	W		I		N		S	
	Φ	$\Delta\Phi$	Φ	$\Delta\Phi$	Φ	$\Delta\Phi$	Φ	$\Delta\Phi$
314	202°	−17°	188°	+28°	168°	−28°	95°	+19°
315	48	− 1					83	+22
320	42	+ 2	183	−11				
326					167	− 5		
333			226	−12	219	− 8	80	−33
353	274	+55			183	−53	88	+36
359					190	+29	80	+47
360					194	+24	81	+36

Of 19 reliable data in the case of local shocks, the deviation is found to be less than 10° in 4 data, from 10° to 20° in 3 cases, from 20° to 30° in 6 cases, and larger than 30° in 6 data. Those deviations are considered to be so large for accidental observational errors, that may probably be concerned with the crustal structure[7,8], the mechanism of earthquake occurrence[9] or the dimension of focal region, but no systematic deviation is detectable in relation to Φ_t, as far as the present data are concerned. Any conclusion, therefore, cannot be derived from these results.

On the other hand, the deviation found in the case of near earthquakes does not exceed the range of observational errors, if the onset of waves was recorded clearly.

3. Structure of the Upper Crust from Local Earthquake Data

In order to deduce the crustal upper structure in the area concerned, the velocity distribution in relation to location and focal depth were investigated using the synthetic data of local shocks obtained in 1954, 1956 and 1959 observations.

a) Relation between the seismic velocities and epicentral orientation measured from some of the stations was examined closely, recognizing no regional character.

b) Fig. 3 shows the relationship between the velocities V_p, V_s and k of the P-, S- and fictitious P–S -waves and the focal depths. It is to be remarked that they were calculated assuming the upper crust to be of uniform medium. As can be seen in Fig. 3, the wave velocities tend to increase gradually with an increase in focal depth. This tendency tells us

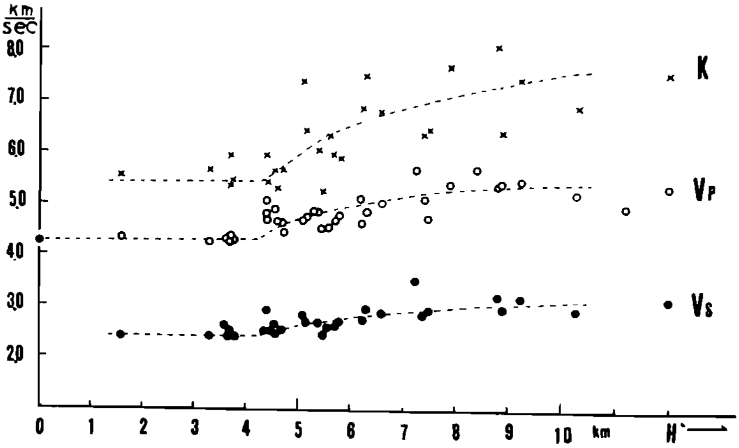


Fig. 3. Wave velocities versus focal depth.

that the crustal structure in this region may be not uniform but complex medium with higher velocities in its lower part. For further discussion, therefore, the structure will be assumed, as a second approximation, to be of horizontal parallel layers.

As stated in the previous paper[3], the surface layer, composed of metamorphic rocks indicating a longitudinal velocity of 4.3 km/sec, is estimated to have a layer thickness of about 4 km, on the basis of the results of seismic prospecting[10] and the velocity values for the focal depth of less than 4 km indicated in the above figure. The corresponding velocity of the transverse waves is found to be 2.4 km/sec. Determining secondly the propagation velocities in the second layer to be adaptable to the velocity distribution shown in Fig. 3, they are calculated as nearly 5.5 km/sec for the P-waves and 3.2 km/sec for the S-waves. The procedure of determination is described in some detail in the previous report.

The velocity of the P-waves in the surface layer and the layer thickness will be confirmed subsequently from laboratory experiments and observations of near earthquakes, respectively.

4. Measurement of Elastic Wave Velocities in Surface Rocks by Means of Ultrasonic Pulse Transmission

Laboratory experiments were made for rock samples collected from outcrops in the vicinity of the observation points in Wakayama region. In order to get more direct evidence on the propagation velocities in the surface layer estimated from local earthquake observation, the elastic wave velocities in the samples of bed rocks were measured by means of ultrasonic pulse transmission. Twelve locations where the materials were gathered are also given in Fig. 1. About 3 materials collected in every location may be regarded to represent the bed rocks of each spot. These are metamorphic rocks termed epidote-chlorite schist, sericite-chlorite schist, quartz-talc schist and graphite-quartz schist, etc.

Measurements were carried out at the Abuyama Seismological Observatory of Kyoto University. The experimental apparatus and technique are the same as reported by Kubotera[11]. Experiments went into operation at room temperature and under ordinary atmospheric pressure. The X-cut $BaTiO_3$ crystals were used as a longitudinal pulse generator of 500 kc-supersonic waves. The materials' lengths along the direction of rock joints ranged from 50 to 100 mm. Fig. 13 gives an example of cathod-ray oscillogram photographed in the measurement.

The obtained velocities diverge from 4 even to higher than 6 km/sec for several kinds of many samples, and no significant difference is recognized for the values in various places. However, the apparent velocity for all of 32 data is estimated as $V_p=4.21\pm0.16$ km/sec by the method of

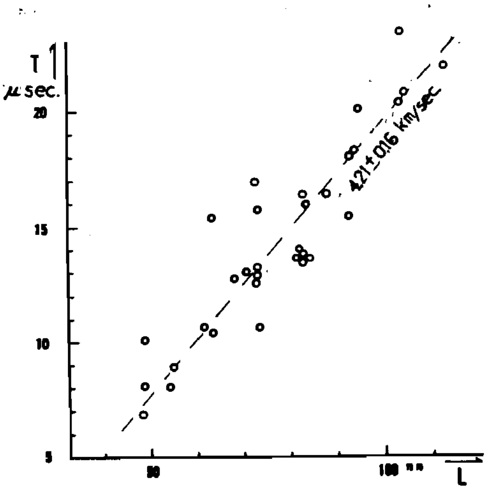


Fig. 4. Transmission times against material's length.

least squares, as indicated from the transmission times plotted against the length of materials in Fig. 4. The above discrepancy between the true and apparent velocities makes the matter complicated. This question remain untouched here, but will be solved in future. It is only to be added that the latter velocity shows a good agreement with the results of seismic prospecting carried out at Shimotsu[10] and the value obtained from local earthquake observation.

5. Structure of the Lower Crust from Near Earthquake Data

Generally speaking, presumption of local structure of the crust solely from observations of near-by earthquakes, seems to be very difficult work, and most of the studies of this kind are limited to obtain a knowledge about the upper part of the structure. To get a clear picture on the whole structure of the crust, some distant stations are required to be established as well as close stations in a confined region[12],[13].

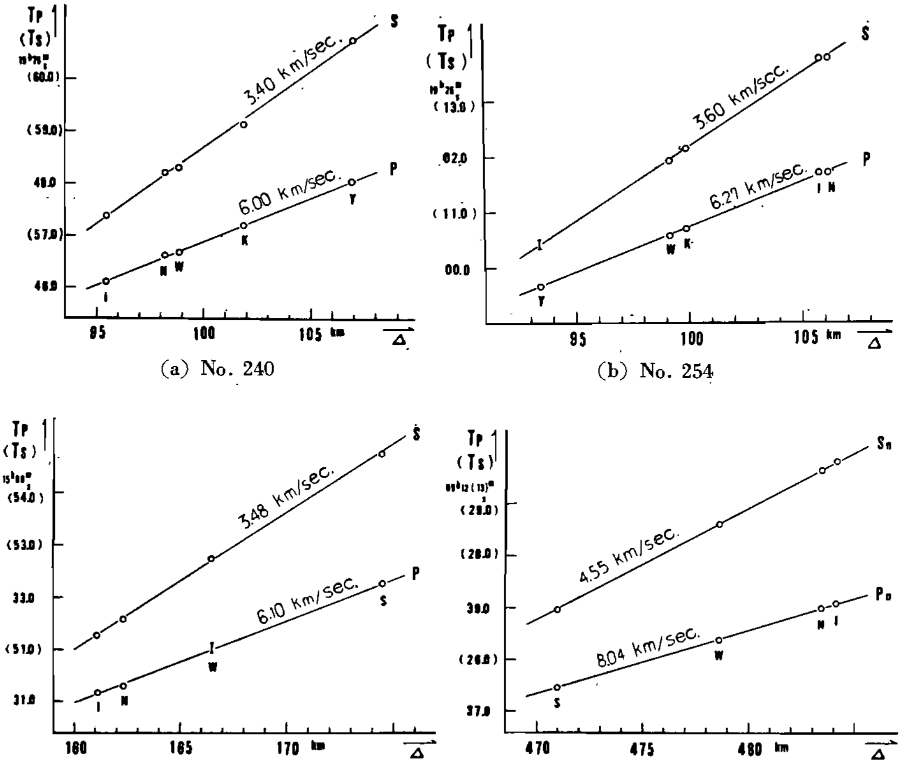
In the present case, however, instead of the prevailing method, we adopted the way to observe near and distant earthquakes with higher accuracy at the afore-mentioned close observation network. The macroseismic data recorded by local meteorological observatories were used synthetically, when available.

(1) *Determination of wave velocities*

Earthquake wave velocities in the deeper crust were determined from observation of 9 near earthquakes having the $P \sim S$ times of longer than 6 sec observed at more than three stations in 1956 and 1959. The observed data are also listed in the annexed table.

a) Time-distance graph method

The epicentres of 4 out of the 9 earthquakes observed can be located by macroseismic observations. Their focal depths were calculated as being within the crust, as shown in Table 4. Fig. 5 illustrates the time-distance



(a) No. 240 (b) No. 254

(c) No. 371 (d) No. 348

Fig. 5. Time-distance curves in 4 near earthquakes.

relation observed at our network stations for these earthquakes. This means the ordinary travel-time curve drawn at a certain scope of distance, as seen through a magnifying glass. The time errors are less than 1/50 sec in well seismograms and about 1/20 sec in other records. The time-distance relations in the above 4 earthquakes are successfully represented as a straight line respectively for the P- and S-waves with satisfactory accuracy. This fact may indicate that there exists no remarkable regional contrast in crustal structure in the district mentioned, considering slight difference between the wave periods in near and local earthquakes.

b) Tripartite stations method

Making use of the arrival time differences of the initial *P*-waves recorded at three observation points in a small area, the apparent velocity and direction of approach of the waves will be effectively estimated. In the present study, this method of tripartite stations was applied to our data of 9 near earthquakes, as their epicentral distances inferred from the $P\sim S$ times are far longer as compared with the span of observation network. The errors accompanying this procedure depend upon the form of triangle connecting the three stations. After Miyamura's method[14], the directional errors were estimated to be $3^\circ\sim8^\circ$ and the errors in the apparent velocities were 5~14% in our case, assuming the reading errors of the arrival times to be 1/20 sec.

c) Table 4 indicates the wave velocities and the directions of approach obtained by either method of the above two. The difference in the values for both methods are within the range of the estimated errors. Fig. 6 gives a vectorial representation of the velocities of initial *P*-waves.

Judging from the epicentral distances, focal depths and velocities,

Table 4. Observed results of near earthquakes.

Shock No.	V_p	V_s	V_p/V_s	Φ	A.M.	Stations	H	λ	φ
240	6.00	3.40	1.77	70°	(1)	I, N, W, K, Y	11	135°32′	35°01′
254	6.27	3.60	1.74	221	(1)	Y, W, K, N, I	10	134 15	33 45
348	8.05	4.55	1.77	233	(1)	S, W, N, I	20~30	132 12	30 41
371	6.10	3.48	1.75	55	(1)	I, N, W, S	10~15	136 13	35 25
244	6.13	3.53	1.74	296	(2)	N, Y, F, Y, W			
304	8.14	—	—	304	(2)	N, S, W			
321	7.08	—	—	285	(2)	S, I, W			
332	12.95	—	—	300	(2)	N, I, W			
369	6.14	3.46	1.77	234	(2)	W, N, I			

V_p, V_s ; the velocities of the *P*- and *S*-waves, in km/sec,
H ; the focal depth in km,
Φ ; direction approach of initial *P*-wave, measured counter-clockwise from eastward at Wakanoura,
λ, φ ; longitude and latitude indicating the location of eicentre,
A.M. ; analytical method, (1) time-distance graph method, (2) tripartite stations method.

indicated by travel time curves in the 4 earthquakes shown in Fig. 5, the initial P-waves in the cases of (a), (b) and (c), and the case of (d), are considered to correspond to the refracted P-waves propagated beneath the interface between the second and third layers, and under the Mohorovičić discontinuity, respectively. That is to say, the propagation velocities determined for the earthquakes, Nos. 240, 254, 371, 244 and 369 are regarded as those in the third layer, and the velocity for the earthquake No. 348 as that in the upper part of the Earth's mantle.

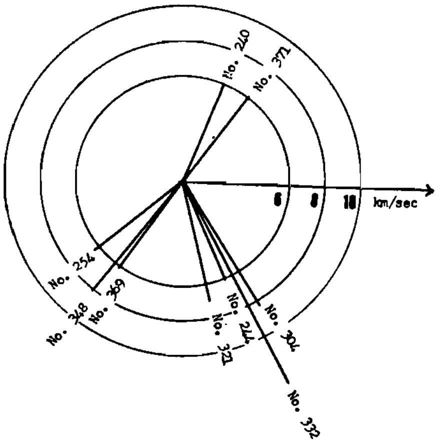


Fig. 6. Velocity and direction of approach of initial P-waves.

Under the assumption of horizontally layered structure, the seismic wave velocities in the respective layers in Wakayama District are assigned as follows, taking account of the results of local earthquake observation and laboratory experiments;

$$\left.\begin{array}{llll} V_p \doteq 4.3\,\text{km/sec}, & V_s = 2.4\,\text{km/sec}, & k = 5.4\,\text{km/sec} & \text{in the 1 st layer} \\ V_p = 5.5\,\text{km/sec}, & V_s = 3.2\,\text{km/sec}, & k = 7.6\,\text{km/sec} & \text{in the 2 nd layer} \\ V_p = 6.1\,\text{km/sec}, & V_s = 3.5\,\text{km/sec}, & k = 8.2\,\text{km/sec} & \text{in the 3 rd layer} \\ V_p = 8.0\,\text{km/sec}, & V_s = 4.5\,\text{km/sec}, & k = 10.3\,\text{km/sec} & \text{in the 4 th layer} \end{array}\right\} \quad (1)$$

(2) *Prominent phases*

In the $P{\sim}S$ interval on seismograms of the said near earthquakes, several prominent phases are detectable as shown in Fig. 13.

The time intervals between the initial P-wave and the later phases concerned are tabulated in Table 5. Fig. 7 shows the intervals $P{\sim}X_i$ plotted against the $P{\sim}S$ times instead of the epicentral distances. As easily seen in the figure, two clear phases with constant time interval irrespective of the $P{\sim}S$ times can be found and picked out. When these two phases are tentatively termed X_I and X_{II} respectively, the time intervals are,

$$P{\sim}X_I \doteq 0.91 \pm 0.03\,\text{sec for } 9 \text{ data in } 5 \text{ shocks, and}$$

Table 5. Prominent phases in horizontal seismograms.

Shock No.	St.	$P \sim S$ sec	$P \sim X_i$ sec					
240	K	11.87			2.30			
	N	11.60	0.92	1.27	2.26			
244	N	9.39	0.91		2.29	3.32		
254	K	11.44			2.38	3.60		
	N	12.06			2.28	3.70		
304	N	6.26	0.93		2.28			
311	W	11.18			2.37	3.29		
317	N	5.67			2.25			
321	S	23.45			2.33		4.00	
332	N	6.10	0.89	1.82			4.58	5.43
348	W	50.20			2.02	2.40	4.18	4.90
	I	50.72			2.00	2.61	4.11	5.40
	N	50.63				2.37	4.08	5.92
	S	49.49		1.24	2.32	3.02	4.10	6.03
369	W	12.00	0.87	1.70	2.32	3.70		
	I	12.67		1.34	2.35	3.60		
	N	12.5		1.71	2.28	3.00	5.11	5.69
	S	12.47	0.94		2.37		4.80	6.03
371	W	19.55	0.92		2.35	3.89		5.05
	I	20.08				3.28		
	N	20.28	0.93		2.32	3.35		5.66
	S	21.43	0.90	1.91	2.37			6.70

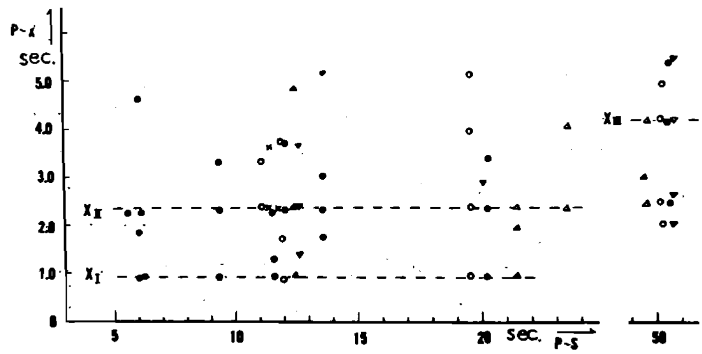


Fig. 7. Time intervals of prominent phases.

$P \sim X_{II} = 2.31 \pm 0.05$ sec for 15 data in 9 shocks.

Moreover, a fairly distinct phase X_{III} is recognized at all stations in an earthquake (No. 348) with longer $P \sim S$ time. The duration time is:

$P \sim X_{III} = 4.12 \pm 0.06$ sec for 4 data.

The characteristics of these prominent phases are discussed in the following.

a) They can be detected at most of the stations in most of the near earthquakes treated here.

b) The time interval between the initial P-wave and them has a certain fixed value without respect to the $P \sim S$ times or the epicentral distances.

c) The phases predominate in horizontal components and cannot be found obviously in vertical one. That is, in the observation in 1956, they were recorded on horizontal seismograms at two stations equipped fully with three component of seismometers, and not at other stations with the vertical only.

d) The wave phases display evidently a kind of polarization. Fig. 8 shows an example of loci of particle motions in the phase X_{II}.

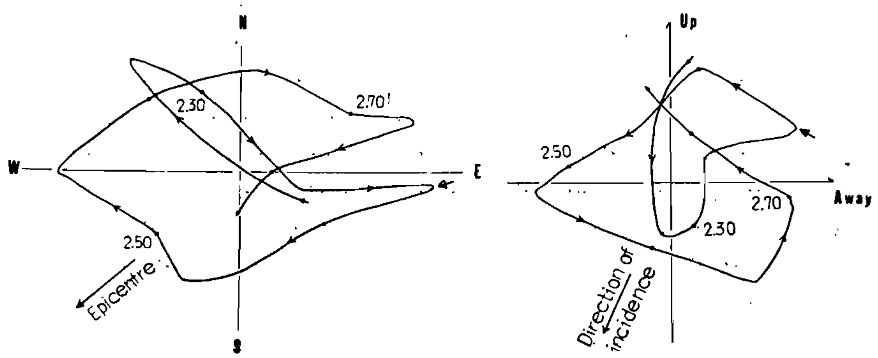


Fig. 8. Loci of particle motions for the phase X_{II}.

The plane of vibration seems to accord with the plane of incidence. Namely, they are presumed to be of SV-type.

On the basis of the above-examined features, we can identify the phases in question as the so-called "*Wechselwellen*" (transformed waves) *PS*, which have thus far recognized in some cases[15,16,17,18]. The first waves in most of the foregoing earthquakes correspond to the refracted P-waves which have travelled horizontally beneath a discontinuity surface, as stated in the preceding sections. The waves PS can therefore be regarded as transformed refraction arrival[19,20] changed from the P-waves at the interface. The similar incidence was observed also in field- and model-experiments[21]. The wave paths for the transformed waves are schematically illustrated in Fig. 9. Taking the velocity of the refracted P-waves into consideration, we can consider, the phases X_I, X_{II} and X_{III} correspond to the cases (1′), (1) and (2), respectively.

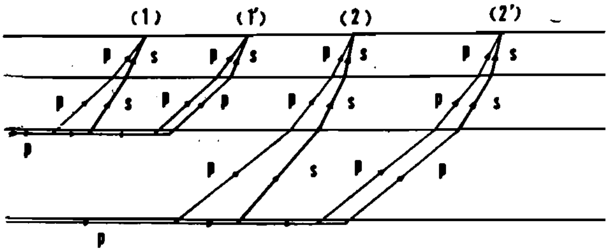


Fig. 9. Schematic representation of wave paths for transformed waves.

e) To confirm the above identification, the theoretical relation between the amplitudes of the refracted P-wave and that of the transformed PS-wave was roughly estimated and compared with the observed values. For the sake of simplicity, the divergence effect of amplitude in relation to travel distance and the effects due to discontinuity surfaces on the way were omitted. Consequently, the amplitudes' ratio of the SV- and P-waves on the occasion of refraction at the bottom interface, and the angles of incidence at the ground surface, play a decisive *rôle* on the relation of both waves which will be recorded on the surface.

The amplitudes' ratio of the refracted SV-wave and refracted P-wave, both of which result from incidence of P-wave at any plane boundary, can be expressed in the following formula[22,23,24]. That is,

$$\frac{A'_{SV}}{A'_P} = -\frac{b^2-1-2a'b-\frac{\mu'}{\mu}(b'^2-1-2a'b)}{2b+b'(b^2-1)+\frac{\mu'}{\mu}(2b'+b(b'^2-1))} \tag{2}$$

$$a=\cot i_p,\quad b=\cot i_s,\quad a'=\cot i_p',\quad b'=\cot i_s',$$

and
$$V_p/\sin i_p = V_s/\sin i_s = V_p'/\sin i_p' = V_s'/\sin i_s', \tag{3}$$

where i_p is the angle of incidence of the P-wave, i_p' and i_s' are the angles of refraction of the P- and SV-waves, V_p, V_s ; V_p', V_s' are the propagation velocities of both waves in two media, and μ, μ' are the rigidities of both media, respectively.

Assuming the densities of media in the four layers to be 2.6, 2.8, 3.0 and 3.3 gr/cm^3 respectively, the ratio of horizontal amplitudes $\bar{A}_{p(H)}$ and $\bar{A}_{SV(H)}$ of the P- and SV-waves, which will be observed at the surface, is calculated for the cases illustrated in Fig. 9, by use of the velocity values in Eq. (1). It is to be remarked here that the ratio A'_{SV}/A'_P in the case of (1) or (2) tends to a certain finite value as the incident angle i_p approaches 90° over nearly 75°, though in geometric optics the respective energies of refracted two waves tend to be infinitesimally small. The results calculated are shown as follows.

	(1)	(1′)	(2)	(2′)
A'_{SV}/A'_p	0.07	0.17	0.18	0.05
$\bar{A}_{SV(H)}/\bar{A}_{p(H)}$	0.08	0.20	0.29	0.08
	(0.35	0.83	1.44	0.42)*

The observed amplitudes' ratios are considerably larger than the above theoretical values. This is, however, not a fatal contradiction for us, as pointed out by Matuzawa[16]. One of the reasons for this is attributable to wave incidence being nearly right angle at the surface, due to existence of a superficial layer. When a thin weathered layer in this region, in which the longitudinal velocity is estimated as about 1,000 m/sec[10], is taken into consideration, the theoretical ratios are computed larger, as indicated by an asterisk. The observed values are in this order of magnitude.

(3) *Deduction of layer thickness from travel times of the PS transformed waves*

Prominent phases detected in the $P \sim S$ interval on the seismograms of near earthquakes are identified as the transformed waves shown in Fig. 9. Several approximate solutions for the travel times of various transformed waves have thus far been obtained[17][18][19]. In our case, however, the exact solution for the transformed refraction arrival can be obtained in a simple form.

We shall here consider a horizontally (n+1)-layered structure. Let

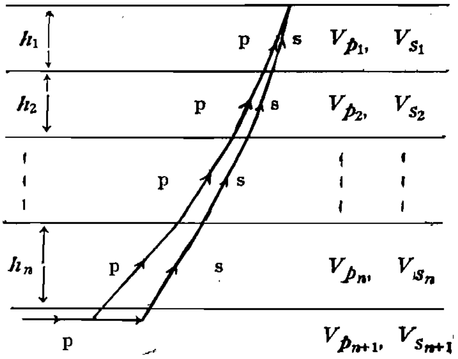


Fig. 10.

the velocities of P- and S-waves in each layer be V_{pj}, Vs_j respectively, and the layer thickness be h_j ($j=1, 2, \cdots\cdots$, n+1). Then, the difference δt_n between the travel time of a transformed refraction PS and that of refracted P-wave, which comes from difference of the indicated two paths in Fig. 10, is expressible as;

$$\delta t_n=\sum_{j=1}^{n} h_j\left(\frac{\tan i_{p_j}-\tan i_{s_j}}{V_{p_{n+1}}}+\frac{1}{V_{s_j}\cos i_{s_j}}-\frac{1}{V_{p_j}\cos i_{p_j}}\right) \quad {}^{20)}$$

$$=\sum_{j=1}^{n} h_j\left(\frac{\cos i_{s_j}}{V_{s_j}}-\frac{\cos i_{p_j}}{V_{p_j}}\right), \tag{4}$$

where $\sin i_{p_j}=V_{p_j}/V_{p_{n+1}}$, $\sin i_{s_j}=V_{s_j}/V_{p_{n+1}}$.

The travel time difference for the respective cases in Fig. 9 are written in the form;

$$\left.\begin{array}{lll}
(1) & \delta t_2=\sum_{j=1}^{2} a_{2j}h_j & a_{2j}=\cos i_{s_j}/V_{s_j}-\cos i_{p_j}/V_{p_j} \\
(1') & \delta t_2'=\sum_{j=1}^{1} a_{2j}h_j & \sin i_{p_j}=V_{p_j}/V_{p_3},\quad \sin i_{s_j}=V_{s_j}/V_{p_3} \\
(2) & \delta t_3=\sum_{j=1}^{3} a_{3j}h_j & a_{3j}=\cos i_{s_j}/V_{s_j}-\cos i_{p_j}/V_{p_j} \\
(2') & \delta t_3'=\sum_{j=1}^{2} a_{3j}h_j & \sin i_{p_j}=V_{p_j}/V_{p_4},\quad \sin i_{s_j}=V_{s_j}/V_{p_4}
\end{array}\right\} \tag{5}$$

Hence, the layer thickness h_j can be estimated on the ground of the previous knowledge about the wave velocities in the respective layers and time intervals between the refracted P-wave and the transformed waves in question. The coefficients are computed as follows using the velocities in Eq. (1). That is,

$$a_{21}=0.217,\quad a_{22}=0.200$$
$$a_{31}=0.202,\quad a_{32}=0.155,\quad a_{33}=0.151.$$

As stated previously, we find,

$$P\sim X_I=\delta t_2'=0.91\pm0.03 \text{ sec},$$
$$P\sim X_{II}=\delta t_2=2.32\pm0.05 \text{ sec},$$

and $$P \sim X_{III} = \delta t_3 = 4.12 \pm 0.06 \text{ sec.}$$

Consequently, we get, applying Eq. (5) to these observed data,

$$\left.\begin{array}{l} h_1 = 4.2 \pm 0.2 \text{ km}, \quad h_2 = 7.1 \pm 0.4 \text{ km}, \quad h_3 = 14.6 \pm 1.2 \text{ km}, \\ \text{and} \quad H = \sum_{j=1}^{3} h_j = 25.6 \pm 1.8 \text{ km}. \end{array}\right\} \quad (6)$$

The above errors come solely from the time errors in the phases mentioned, but will become larger if the accuracy of velocity values are taken into account. h_1, the thickness of sedimentary layer, agrees well with the values estimated from local earthquake observation. H may be regarded as the depth of Mohorovičić discontinuity in this region. This value is in fairly good accord with the crustal depth over the Kii Peninsula[25,26,27] deduced from other methods of analysis on natural earthquakes.

6. Crustal Structure in Wakayama District and Some Related Problems

The crustal structure in Wakayama District as deduced from close observations of local and near earthquakes and some laboratory experiments, is given in Fig. 11, assuming the crust to be of a horizontally layered structure. This is consistent with the structure in northern Kinki District derived from the results of recent explosion seismic observations[28].

In the next place, the focal positions of local shocks are plotted in a north-southern profile as shown in Fig. 12, to clarify the spatial distribution of foci in relation to the crustal structure. The vertical and hori-

		V_p	V_s	
26 km	4 km	4.3 km/sec,	2.4 km/sec	sedimentary layer
	7 km	5.5 km/sec,	3.2 km/sec	granitic layer
	15 km	6.1 km/sec,	3.5 km/sec	basaltic layer
				Mohorovičić discontinuity
		8.0 km/sec,	4.5 km/sec	ultrabasic layer

Fig. 11. Crustal structure in Wakayama District.

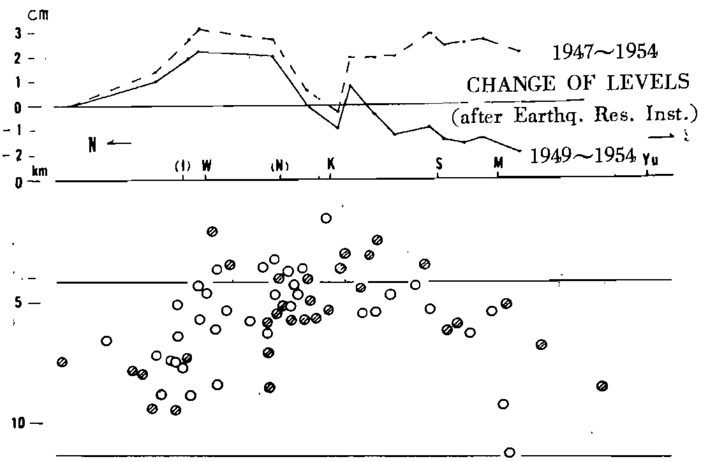


Fig. 12. Spatial distribution of local shocks and change of ground levels.

zontal scales are equally reduced. The respective foci were located assuming the upper crust to be of a uniform medium in place of the deduced horizontal parallel layers. However, the errors resulted from the incorrect assumption are found, after some calculation, to be negligibly small in the epicentre's location and less than 1 km in the focal depth. General view of the focal distribution, therefore, may be not affected. The open circles show the foci determined by our observations in 1954, 1956 and 1959, and the hatched circles indicate the hypocentres estimated by observations at four stations of the Earthquake Research Institute in 1952, 1953 and 1954[29]. The formers are micro-earthquakes having the released energy of $10^{10}\sim10^{12}$ ergs, while the latters are considerably larger earthquakes. A similar tendency is recognized between the states of focal distribution for both kinds of earthquakes. It is a remarkable fact that in northern part of Wakayama region all of these earthquakes occurred in the granitic and sedimentary layers. This contrasts sharply with the sub-crustal distribution of foci of local earthquakes in Kwantô District[14,30].

It is also noteworthy that the spatial distribution of foci in Wakayama region shows an interesting concentration. Namely, the focal depths are shallowest near Kainan City and deeper northwards and southwards. For reference's sake, the appearance of a crustal deformation during 1947～1954 indicated by the results of precise level surveys[2], which were carried out by the Earthquake Research Institute, is also added in Fig. 12. Further results obtained by the Institute show that no great change occurred in the ground levels during 1955~1959[31]. Number of occurrence of local shocks decreases gradually during the same period. In this region, the crustal deformation may probably have some relation with the state of focal distribution of micro-earthquakes.

7. Summary

With a view to deduce the crustal structure in Wakayama District, close observation of local and near earthquakes was carried out over the area. Laboratory experiments on surface rocks were also made to get reference data on seismic velocities. The results obtained are summarized in the following.

(1) In local earthquake observations, the propagation velocities of the *P*- and *S*-waves in the surface and second layers and the first layer thickness were estimated from a velocity-focal depth relation for many shocks. The horizontal direction of approach of initial wave observed at each station, showed a fairly large deviation from the epicentral orientation determined by a travel-time analysis.

(2) The elastic wave velocities in many samples of bed rocks collected in this region, were measured by ultrasonic pulse transmission. The supersonic velocities in the respective materials were diverse and considerably high, but the apparent velocity for all data was calculated as about 4.2 km/sec.

(3) In the observation of near earthquakes, the seismic wave velocities in the third and fourth layers were determined by time-distance curves and tripartite stations method. On the seismograms of near earthquakes, several prominent phases were found at the $P{\sim}S$ interval. These phases could be identified as transformed refraction arrival *PS*, judging from their constant time intervals from the initial wave, their polarization and amplitude relation. The thickness of each layer was estimated by use of the time intervals.

(4) The crustal structure in Wakayama District deduced from local and near earthquake observations and laboratory experiments, is as follows:

$V_p=4.3$ km/sec, $V_s=2.4$ km/sec, $h_1=$ 4 km for the sedimentary layer,

$V_p = 5.5$ km/sec, $V_s = 3.2$ km/sec, $h_2 = 7$ km for the granitic layer,
$V_p = 6.1$ km/sec, $V_s = 3.5$ km/sec, $h_3 = 15$ km for the basaltic layer,
$V_p = 8.0$ km/sec, $V_s = 4.5$ km/sec, for the mantle surface.

The crustal depth to the Mohorovičić discontinuity in this region was estimated to be about 26 km.

(5) The spatial distribution of foci of micro-earthquakes was investigated in relation to the crustal structure. Generation of local shocks in northern Wakayama District was found to be confined above the granitic layer.

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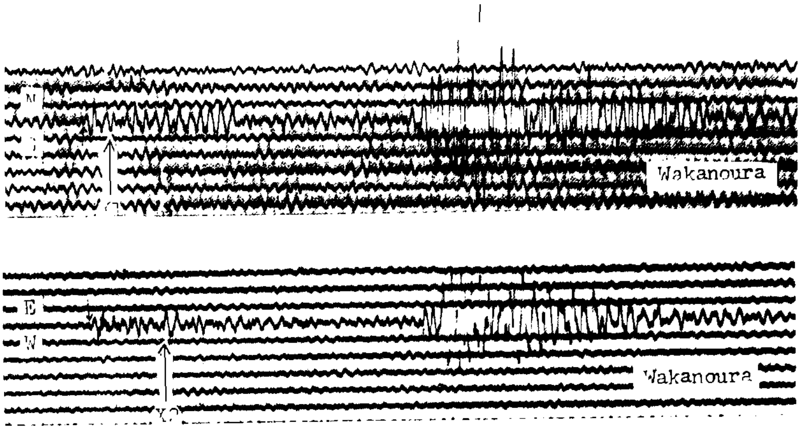
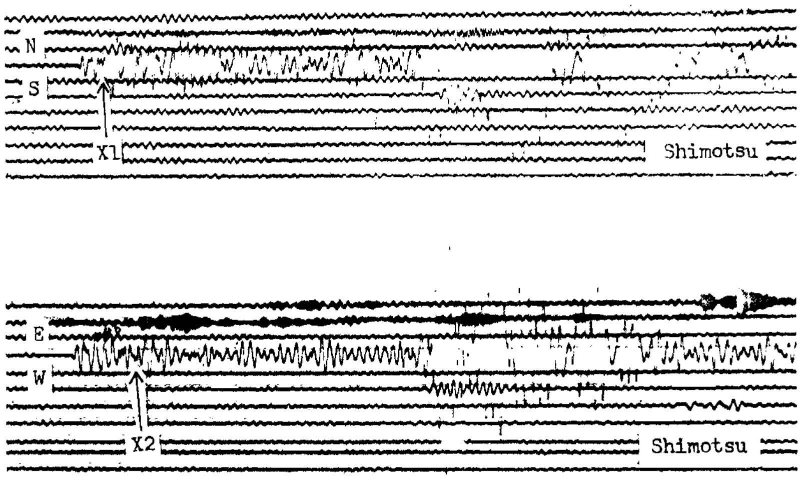

N
Wakanoura
E
W
Wakanoura

(a)


N
S
X1
Shimotsu
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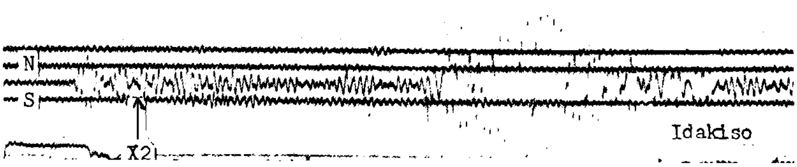
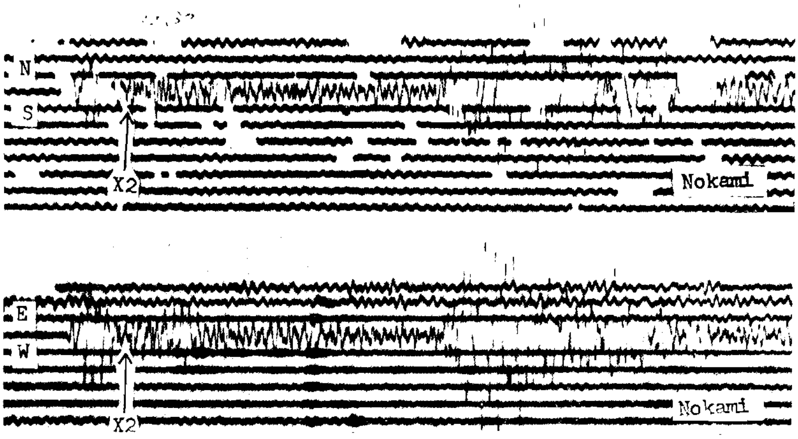
W
X2
Shimotsu

(b)


N
S
X2
Idakiso

(c)



(d)

Fig. 13 (A). Examples of seismograms in a near earthquake. (No. 369. Aug. 31, 1959, 12 h 42 m), original×8/10. (a) Wakanoura, (b) Shimotsu, (c) Idakiso, (d) Nokami.

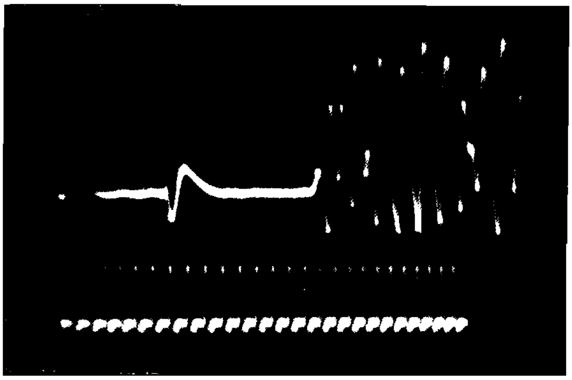


Fig. 13 (B). An example of cathod-ray oscillogram obtained in the case of ultrasonic transmission measurement.

Annexed Table. Observed data of seismometric observations in Wakayama District.

No.	Date	Time	W			I (L_2)			F			N			K			Y			S		
			P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S
	1954	h m																					
121	Nov. 29	16 11				28.57	+	3.83				28.02	−	3.56				27.40	−	3.02			
122	29	16 15				34.63	+	1.22				35.21	−	1.81				35.1	(−)	1.78			
123	29	16 23				45.59	+	0.93				46.14	−	1.15				46.6	+	1.62			
124	30	09 21				56.88	−	1.00				57.47	−	1.65				57.98	+	2.46			
135	Dec. 1	09 00				08.94	−	1.44				09.37	−	2.02				08.19	+	1.18			
136	1	10 12				19.95	+	1.90				20.35	−	2.17				18.59	+	0.92			
137	1	10 15				10.59	−					11.13	+					12.16	+				
140	1	11 18				44.64	+	0.6										46.31	−	1.84			
151	2	10 34				48.57	+	0.81				49.13	−	1.01				49.56	(+)	1.75			
	1956																						
201	Apr. 13	16 13				08.16	+	(4.4)				07.48	+	3.78	07.09	+	3.60	06.65	+	3.27			
202	14	13 38				40.65	+	1.45	40.04	+		41.02	(+)		40.18	(−)	1.36						
206	15	16 03	31.7	−		32.52	−		31.92	−					31.63	−		30.82	−				
207	16	13 28	49.59	+	0.84	50.00	+	1.0				50.18	−	1.34	49.41	+	0.79	49.79	−	1.1			
217	19	09 25	04.04	+		04.72	+	1.26	04.32	+	1.04	05.33	+	1.68	04.84	−	1.18	04.80	+	1.32			
220	19	14 47	55.66	−	1.10	55.13	+	0.80	55.37	+	0.92	55.76	+	1.18	55.82	+							
222	19	18 25	37.33	+		38.16	+	2.26	37.54	(+)	1.64	38.33	+	2.10	37.11	+	1.66	36.24	+	1.17			
223	19	19 07	29.04	+	1.05	29.6	+	1.23	29.22	−	0.98	30.10	+	1.77				29.08	+	1.11			
224	20	09 50	41.30	+	0.87	41.66	+	1.13	41.21	−	0.94	42.24	+	1.67									
228	20	15 33	23.58	+	0.91	24.46	+	1.30	24.02	+	1.14	25.04	+	1.90	24.49	+	1.36	24.46	+	1.34			
230	20	17 52	06.91	+	0.53	07.25	−	1.12	06.91	−	0.66	07.88	+	1.26	07.30	+	0.98	07.44	+				
236	21	16 33	26.20	+		27.01	+	2.17	26.35	+	1.67	26.80	−	1.66	25.90	(−)		25.02	+	1.27			
247	22	12 44	56.75	+		56.89	+	4.45	56.49	+		56.28	+		55.70	+	3.69	55.	+	3.51			
248	22	15 51	20.76	+	0.87	21.75	−	1.33	21.32	−	0.93	21.5	+	1.80	21.65	−	1.32	21.72	+	1.28			
249	22	16 14	01.08	+	1.16	01.42	−	0.92	01.12	+	1.19	01.90	+	1.57									
250	22	17 03	21.40	+		22.03	−	1.19	21.46	(+)	0.77	22.29	+	1.61	21.45	−	0.79						
251	22	17 11	53.75	+		54.43	+	1.11	53.74	+	0.80	54.50	+	1.47									
253	22	17 40	39.32	+	1.30	39.33	+	1.25				40.22	+		39.93	+	1.72	40.5	+				
	1959																						
314	Aug. 17	11 43	34.47	+	0.92	35.51	+	1.59				36.25	−	2.09							36.	+	1.59
315	17	11 58	20.12	−	1.21	21.		1.57				21.39	−	2.13							21.	+	2.06
320	18	13 17	10.91	−	0.97	11.80	−	1.58				12.50	−	2.21							12.	−	1.90
326	20	12 38	00.57	−	0.95	01.46	+	1.38				02.13	+	1.92							02.	−	1.69
333	21	14 18	18.68	−	1.68	19.44	−	2.33				19.32	(+)	2.53							18.	+	1.15
335	21	16 03	19.09	−	0.99	20.05	(−)	1.73				20.43	−	2.16							19.	+	1.20
353	25	15 47	24.85	+	1.04	25.74	+	1.85				26.44	−	2.32							25.	−	1.34
359	28	12 22	19.35	(+)	0.92	20.28	+	1.68				20.43	−	2.02							18.	−	0.87
360	29	09 45	34.20	−	1.28	35.04	(−)	1.82				35.31	−	2.05							33.93	−	1.04
	1956																						
240	Apr. 21	19 26	46.63	+	11.64	46.10	+	11.27				46.60	+	11.60	47.18	+	11.87	48.02	+	12.63			
244	22	11 30	27.25	−	10.28	26.85	−	10.43	26.79			26.03	−	9.39				26.18	−	9.47			
254	23	19 26	00.57	+	11.37	01.70	+	12.05				01.69	+	12.06	00.70	−	11.44	59.66	−	10.64			
	1959																						
304	Aug. 12	16 36	47.84	+	7.46							46.42	+	6.26							46.68	+	5.82
321	18	14 14	04.91	−		04.72	−	25.29													03.62	−	23.45
332	21	13 13	28.24	+	6.86	28.02	+	6.92				27.57	+	6.10							27.	+	6.34
348	25	09 12	38.40	+	50.20	39.10	+	50.72				39.00	+	50.63							37.47	+	49.49
369	31	12 42	27.52	+	12.00	28.40	+	12.67				28.23	+	12.5							28.	+	12.47
371	31	15 00	32.2	−	19.55	31.18	−	20.08				31.31	−	20.28							33.35	−	21.43

No.	Km			Ko			Ko′			D			Sa			R_2		
	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S
121	28.14	+	3.61							28.46	+	1.20						
122	34.10	+	0.9	34.20	−		34.26	−	1.03									
123	45.66	(+)	0.94	45.84	−													
124				57.35	−	1.55												
135				08.03	−					07.09	+	0.93	08.27	+	1.0			
136	19.4	−	1.48	18.98	−	1.05				19.33	(+)	1.52						
137	11.18	+		11.32	+					11.25	−		10.77	−				
140	45.32	−	1.02	45.43	−		11.36	+	1.25	45.40	(−)	1.25	44.93	+	0.78			
151	48.53	+	0.76	48.82	−	1.13	45.53	−	1.20	48.86	+	0.94	48.50	+	0.9			
201				07.26	+	4.00												
202				39.83	−	1.05	39.86	−	1.12									
206				31.37	−		31.38	−	2.00									
207				49.26	+	0.68	49.27	+										
217				04.32	+	0.98	04.37	+										
220				56.09	+	1.20												
222				36.83	+	1.47												
223				28.75	+	1.00												
224				41.19	−													
228				24.01	+	1.21												
230				07.05	(+)													
236				25.69	+	1.61	25.72	+	1.60							26.99	−	
247				55.99	+	3.80	55.99	+										
248				21.43	−	1.07												
249				01.30	+	1.31												
250				20.89	+		20.90	+	0.64							22.34	(+)	1.62
251				53.21	+	0.74	53.23	+										
253				39.73	+	1.47	39.76	+								40.28	+	1.81

No.	R_3			L_1			Ni			Kh			Ka			T			M			Yu		
	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S	P	I.M.	P~S
137																			12.86	−	2.36			
201	06.78	+	3.12	05.43	+	2.68				07.20	(−)	3.94												
202	39.84	(+)	1.25	41.83	−	2.12	39.70	−	1.25	40.06	−	1.32												
206	30.56	−		32.01	−					31.50	−		31.79	−	2.06	32.62	−	2.92	30.38	−	1.45	31.20	(+)	2.03
217				06.37	−	1.87	04.01	+					04.78	−	1.16	05.48	+	1.74						
220				57.89	+																			
236				26.03	−								26.15	+										
247	55.41	+		54.19	+	2.80													54.99	+	3.38	53.97	+	2.5
250													21.53	(−)										

P ; commencement time of initial P-wave
P~S ; P~S interval
\+ ; "push" in the direction of initial motion
− ; "pull" 〃 〃

The data obtained in the stations of the Earthquake Research Institute ; Ko, Ko′, D, Sa, R_2, R_3, L_1, Ni, Kh, Ka, T, M, Yu, were furnished by the courtesy of the Institute.

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